ALMA Technology, Science and Status Abstract Book

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The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, Japan and North America in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organisation for Astronomical Research in the Southern Hemisphere, in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).

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ALMA Construction Status and Science Perspective

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The Atacama Large Millimeter/submillimeter Array (ALMA) reached the halfway point in construction in 2008 with the completion of the major infrastructure at both the 3000m altitude Operations Support Facility (OSF) and at the 5000m Array Operations Site (AOS). As the year closed, twelve production antennas were at the OSF both at the antenna contractor facilities and at the Technical Building. Initial testing has confirmed that antenna performance is superlative. Both massive transporters have been delivered and have moved antennas around the ALMA site. The first quadrant of the main correlator has been installed at the AOS, joining the NAOJ correlator installed at the end of 2007. About four dozen antenna foundations have been poured at the AOS, ready for the installation of antennas brought up the completed 43km road during the coming months. Sensitive receivers based on the ALMA design already produce scientific results on antennas around the world, including the ARO and CARMA in the U. S. The first Front Ends, populated with receiver cartridges covering atmospheric bands between 3mm and .45 mm, have been tested and installed in the first production antennas. The first of the Water Vapor Radiometers will be installed on the ALMA Front Ends soon. The three Front End Integration Centers will deliver further tested and calibrated units to populate the stream of incoming production antennas. The first back ends have also been tested and installed in those antennas; that production line continues. Software and hardware tests that have occurred at the ALMA Test Facility in New Mexico will transfer to the production test facility at the OSF in the next few months. The production photonic Local Oscillator components will be installed and interferometry in Chile will begin. Very soon the production system at the AOS will commence commissioning and astronomical validation.

ALMA Band	Frequency Range (GHz)	Responsible Organization	Delivered Receiver Temperature K
3	84-116	HIA, Canada	37 SSB
4	125-163	NAOJ	Testing
6	211-275	NRAO, USA	40 SSB
7	275-373	IRAM, France	50 SSB
8	385-500	NAOJ	Testing
9	602-720	NOVA	100 DSB
10	787-950	NAOJ	Under development

The ALMA Front End

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The ALMA project, a collaboration of North American, European, Japanese, and Taiwanese scientific agencies, is building the ALMA radio astronomy array, consisting of (1) a main array of fifty 12-meter diameter antennas and (2) a compact array (ACA) of four 12-meter and twelve 7- meter antennas. The instrument is to be used for observing astronomical sources in ten bands from 31 to 950 GHz at a 5000 meter elevation site in the Atacama Desert of Chile.

The ALMA Front End is an assembly of multiple mm and sub-mm wavelength receivers with an amplitude calibration device and water vapor radiometer. The spectrum from 31 to 950 GHz which is observable through the Earths atmosphere is divided into ten receiver bands. In the initial construction phase, seven bands are currently funded and all use SIS mixers:

The 1-meter-diameter cryostats from Rutherford Appleton Laboratory (RAL, UK), will house these receivers and accommodate the remaining four bands when they are eventually funded. Unlike previous generations of mm and sub-mm receivers, the ALMA Front End is electronically tunable in all respects. The SIS mixers use Nb/Al-AlOx/Nb tunnel junctions and are of advanced fixed-tuned design with wide IF bandwidth. For bands 4 and higher, wideband varistor frequency multipliers are mounted on the 110K stage of the cryostat. LO power to drive the multipliers is provided by a chain of band-specific active multipliers, filters, and amplifiers, with a YIG-tuned oscillator as the fundamental signal source. A final variable-gain MMIC power amplifier provides adjustable LO drive power for the multipliers. The LO drive signal to the multipliers is phase- locked to the output of a reference photomixer which is driven by two centrally-located phase- locked infrared lasers over a phase-stabilized optical fiber. The ALMA Front End meets the extremely stringent phase noise and phase stability specifications needed for operation up to 950 GHz on baselines up to 15 km.

The status of assembling and testing the first ALMA Front Ends in the laboratory and with the ALMA antennas will be presented. This work has been performed over a period of several years as a widely distributed effort coordinated by the NRAO, the European Southern Observatory (ESO), and the NAOJ. Other institutions with significant participation include the HIA, IRAM, NOVA, Onsala Space Observatory (OSO, Sweden), RAL, the Centro Astronomico de Yebes (CAY, Spain), the University of Cambridge / Astrophysics (CA, UK), and the Academia Sinica (Taiwan).

Science at the Arizona Radio Observatory with ALMA-Style Frontends

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Over the past few years, the Arizona Radio Observatory (ARO) has been incorporating ALMA-style sideband-separating mixers into their receivers. In 2006, ARO implemented a 1mm ALMA-Band 6 (215-275 GHz) receiver at the Submillimeter Telescope (SMT) on Mt. Graham in collaboration with the National Radio Astronomy Observatory (NRAO). This new receiver has given record-breaking sensitivities with total system temperatures at 1mm as low as Tsys 106 K, single sideband, on the sky at moderate elevations. Image rejection typically has been 15-20 dB with excellent baseline stability. This receiver has subsequently become a dual polarization facility instrument at the ARO-SMT featuring a steerable 4-8 GHz IF and the option of 2 or 4 IF channels for simultaneous observations of both upper and lower sidebands in both polarizations, if desired. Since its installation, this receiver has been producing a wide variety of novel results, ranging from detection of new interstellar molecules at the mK level in the 1mm band (e.g. PO, PH3, and A1O) to extragalactic observations of HCN towards ULIRGS. This system has also played a critical role in the 1mm VLBI detection of SgrA* with 40 microarcsecond resolution. It has been used to make sensitive images of Bok globules in CO and 13CO and to probe the structure of circumstellar shells of supergiant stars such as VY Canis Majors. These scientific results will be discussed. In Spring 2008, the ARO also implemented a new 0.4 mm Band 9 receiver at the SMT based on ALMA-type mixers provided by Space Research Organization Netherlands (SRON), as well as a new 3 mm Band 3 receiver employing ALMA-type mixers supplied by Herzberg Institute for Astrophysics (HIA). Preliminary data taken with these systems showed excellent improvement in sensitivity, as well. These two receivers are currently being upgraded to dual polarization facility instruments. New scientific results from these receivers will be presented.

The ALMA Test Facility in Retrospect

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The ALMA Test Facility (ATF) is located at the Very Large Array site just outside of Socorro, New Mexico. The ATF is composed of two prototype antennas working as single dishes and in interferometric mode. The ATF has been functioning as test and development platform for several years and for the past year it has been operating as a mini-observatory. Software development is generally scheduled during the day, operators and commissioning astronomers work during the night to verify software, hardware and develop commissioning procedures. The ATF will close on December 20th, 2008 when ALMA activities are ramping up strongly. I will discuss the ATF, what was done and the benefits to the ALMA project to have this separate operational facility.

The ALMA Real Time Control system

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The Atacama Large Millimeter Array (ALMA) is a revolutionary millimeter and sub-millimeter array being developed on the Atacama plateau of northern Chile. An international partnership lead by NRAO, ESO, and NAOJ this powerful and exible telescope will provide unprecedented observations of this relatively unex- plored frequency range.

The control subsystem for the Atacama Large Millimeter Array must co-ordinate the monitor and control of at least sixty six antennas (in four di?erent styles), two correlators, and all of the ancillary equipment (samplers, local oscillators, front ends, etc.). This equipment will be spread over tens of kilometers and operated remotely. Operation of the array requires a robust, scalable, and maintainable real time control system.

The real time control system is responsible for monitoring and control of any de- vices where there are xed deadlines. Examples in the ALMA context are antenna pointing and fringe tracking. Traditionally the real time portion of a large software system is an intricate and error prone portion of the software. As a result the real time portion is very expensive in terms of e?ort expended both during construction and during maintenance phases of a pro ject.

The ALMA real time control system uses a Linux based real time operating system to interact with the hardware and the CORBA based ALMA Common Software to communicate in the distributed computing environment. Mixing the requirements of real time computing and the non-deterministic CORBA middleware has produced an interesting design. We discuss the architecture, design, and implementation of the ALMA real time control system. Highlight some lessons learned along the way, and justify our assertion that this should be the last large scale real time control system in radio astronomy.

Atmospheric phase correction for ALMA with water-vapour radiometers

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Phase uctuations due to the irregularities in the troposphere impede sub- mm interferometric observations by reducing the time available for observations to stable-weather conditions and restricting the maximum usable baseline length in even the best conditions. To reach its goals of resolution as ne as 5 milli- arcseconds and high operating efciency, ALMA will need to effectively correct these phase uctuations. In this talk I will review ALMAs strategy, which con- sists of periodic switching to nearby calibrators (fast-switching) combined with measurements from 183 GHz Water Vapour Radiometers (WVRs). I will present the progress on the development of Bayesian algorithms that will convert WVR outputs into antenna phase correction factors. These algorithms can optimally in- corporate information about weather conditions that is available (such as ground pressure, temperature, humidity) while marginalising over parameters that we have few constraints on (such as the height of the turbulent layer and total water vapour content of the atmosphere). I will also present simulations that model the perfor- mance of individual radiometers and the overall ALMA phase correction strategy.

How to Choose a Walsh Function

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The ALMA project uses nested Walsh function phase switching as a way of separating upper and lower sidebands, and within the inner loop to minimize the impact of spurious signals and DC offsets entering in the signal path between the first mixer and the digitizer. The inner loop switching is introduced as a 180-degree phase modulation at the first local oscillator, and is demodulated as a sign reversal immediately after the digitizer. A spurious signal leaking into the signal path of this inner loop will appear, after demodulation, as an unwanted Walsh function signal superposed on the wanted data. Even if the spurious signals at different antennas are correlated, then with orthogonal Walsh functions at different antennas, these spurious signals should cancel perfectly at the correlator.

If the synchronization of the modulation and demodulation is perfect, both within one antenna and between different antennas, then different Walsh functions are perfectly orthogonal. However, in practice small offsets in the relative timing of the modulation and demodulation waveforms are inevitable, due perhaps to different cable lengths, or differences in propagation time of signal or switching waveform through analog or digital circuitry. This has two implications: (1) there will be a small loss in wanted signal, equivalent to a small loss of coherence, and (2) unlike sinusoidal waveforms of different frequencies, Walsh functions of different sequencies do not necessarily remain orthogonal in the presence of relative timing offsets.

In general precisely N^2 /3 of all N.(N-1) /2 possible cross-product pairs in a set of N Walsh functions remain orthogonal in the presence of a time shift. For ALMA, there are 10^{36} ways of choosing a set of orthogonal functions for 64 antennas from a set of 128 Walsh functions, but nevertheless it is not possible to find any set of functions where more than 80% of all cross-product pairs within that set remain orthogonal. So, with any practical choice of functions the cancellation of correlated spurious signals will not be perfect.

Different sets of Walsh functions behave better or worse in the presence of timing offsets, both for loss of signal and for loss of orthogonality. A given set of functions chosen for lowest loss of signal coherence is not the best set to minimize spurious signal leakage, and vice versa.

A strategy is suggested to choose a set of functions having the best compromise between loss of sensitivity and immunity to spurious crosstalk. The expected performance is presented.

The ALMA Data Transmission System

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The ALMA Data Transmission System, or DTS, transmits 3-bit digitized intermediate frequency (IF) astronomical data signals from an antenna to a centrally located correlator. The digitized IF data is divided equally across four almost identical transmission elements. Each element formats the parallel data from an IF digitizer for serial transmission over three 10 Gb/s optical fiber channels. A total of twelve serial channels for each antenna are multiplexed onto a single 120 Gb/s serial stream. This stream is demultiplexed and converted back into parallel data at the receiver elements prior to being transferred to the correlator.

The Virtual Parallel Bus system is defined by a channel signaling protocol. This protocol is based upon a 160-bit frame structure using line coding employing scrambling techniques. Each frame consists of a first frame marker, or metaframe bit, a synchronization word, a sequence word, the payload, and a checksum. Modulo-2 addition of the frame with a pseudo random pattern scrambles the data to provide adequate recovery timing information and a reduction of any low frequency content which may compromise the timing recovery.

By taking advantage of current telecommunications industry standards, Commercial Off The Shelf (COTS) components are used throughout the ALMA DTS.

The Science Case for ALMA Band 1

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The Atacama Large Millimeter/Submillimeter Array (ALMA) "Band 1" is nominally 31.3 GHz to 45 GHz, and was one of the 10 bands originally envisioned for ALMA. The rebaselining of ALMA earlier this decade, however, caused Band 1 to be removed from the first line-up of receiver bands that will be available when ALMA soon begins operations. The science cases for the availability of Band 1 on ALMA, however, remain very strong. In this presentation, we will briefly summarize the primary science drivers for building Band 1 as part of upcoming ALMA Development in the next decade. These drivers include high-resolution observations of the Sunyaev-Zel'dovich Effect, decrements in the cosmic microwave background caused by hot electorns in galaxy cluster haloes. Also, Band 1 can be used to observe magenetic fields in star-forming cores from Zeeman splitting of molecular emission, rotational transitions from complex organic molecules, thermal emission from large grains in protostellar disks and electric dipole emission from very small, spinning dust grains, among other uses. We also describe early discussions on collaborations to produce the Band 1 receivers, should the astronomical community deem them worthwhile as part of the ALMA Development programme.

Absolute Antenna Gain Calibration for ALMA

Wm. J. Welch (UCB; welch@astro.berkeley.edu) and James Gibson

Gain calibration for antennas in an array is aided by the fact that the sensitivity in cross-correlation is proportional to the geometric mean of the gains of the separate antennas. One can use as one of the elements an antenna whose gain is small but accurately known. The knowledge of the gain of the small antenna can be transferred to the other, larger, antennas in the course of an observation of a compact radio source. Altogether one obtains the flux of the compact source, and the gains of the larger antennas in the array. In addition to the gain of the small antenna, one must know accurately the output receiver scales of the small antenna and the other antennas. This idea has been applied successfully at both 1 cm and 3 mm wavelengths. We describe the necessary components, some precautions, and some results. We also suggest how the technique may be applied to ALMA.

Chapter 1

Information

1.1 Political

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, Japan and North America in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organisation for Astronomical Research in the Southern Hemisphere, in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).

1.2 Technical Description (Richard E. Hills)

ALMA: the numbers

Main Array: at least fifty 12m antennas on 170 foundations, baselines from 20m to >15km. 28 configurations in main sequence with additional sets more extended N-S.

Compact array: twelve 7m antennas on 18 pads (two configurations with baselines from 10 to 40m) plus four fixed 12m antennas for total-power observations.

We have two transporters for moving the antennas.

Each antenna contains one front-end, including a cryostat and calibration devices, and one back-end antenna article, which consists of two racks analogue and digital.

The cryostat contains up to ten cartridges (only 7 in baseline ALMA) each covering one frequency band. Overall frequency range is 31 to 950GHz. Only one band observes at any time but rapid switching between any two is possible.

Each cartridge receives two polarizations and down-converts the signals to an intermediate frequency with eight GHz of bandwidth per polarization. (Some cartridges are single-sideband and some double.)

The Local Oscillator signals are transmitted to the antennas on optical fibres with a round-trip measurement to correct for length changes. There are four independent LO systems so that the compact array, the total power antennas and two sub-sections of the main array (sub-arrays) can be making independent observations.

Each of the 8GHz-wide IF bands is divided into four 2GHz-wide basebands which are digitized at four Gsamples/s, with three-bit resolution, and transmitted on optical fibres. Total data rates is therefore 96Gbits/s per antenna. With formatting bit rate is 120 Gb/s.

On arrival at the central building the data are recovered and processed in two correlators one has 16-inputs and the other 64-inputs. All antennas can feed both.

The 16-element correlator is normally used for the compact array and can work with two subarrays. It is an FX correlator (transform then correlate) with 3-bit input and 4 bits in the correlation. The transforms have a million points (strictly 220) and operate on the eight basebands from on the 16 antennas. The correlator then generates 120 cross- and 16 auto-correlations for each baseband. These are passed to the (special-purpose) data processing computer at up to 0.6GB/s per baseband.

The 64-element correlator is normally used for the main array but can also take inputs from the compact array. It can operate with at least six independent sub-arrays. It is an XF correlator but the correlator proper is preceded by the Tunable Filter Bank. This can select sub-bands from the 2GHz-wide basebands in a flexible manner. From each of these the correlator then generates 2016 cross- and 64 auto-correlations (which requires 1.7x1016 operations per second). Either 2-bit of 4-bit resolution is used and the sampling can be Nyquist or twice Nyquist. The data is then dumped to a group of processors which do the transforms and carry out integration and data compression..

Both correlators have minimum dump rates of 16ms for cross-correlation and 1ms for auto-correlation but the data rates for modes with large numbers of channels are then far to high for transmission and storage. The systems are designed for a maximum data rate of 64 MB/s and archive system assumes a mean data rate of 6.4 MB/s (total from both correlators).